Direct Fusion Drive
For Europa Exploration

Princeton Satellite Systems, Inc.
6 Market Street Street, Suite 926
Plainsboro, NJ 08536
Phone: 609-275-9606
Fax: 609-275-9609
Email: map@psatellite.com
Web: www.psatellite.com
Executive Summary

Exploration of the Jovian system has garnered popularity and interest, as three of the four large Galilean satellites are suspected to contain sources of water [1]. Several missions to explore one of them, the moon Europa, have been proposed. Two of these are the NASA Europa Clipper mission and the NASA Europa lander mission. The Europa Clipper mission would place a spacecraft in orbit around Jupiter to perform a detailed investigation of Europa. Key scientific objectives of such a mission include characterizing the ice shell and any subsurface water on Europa, understanding the habitability of Europa’s ocean by studying its composition and chemistry, and understanding the formation of surface features to characterize high science interest areas for future observation and exploration [2]. Another mission is the Europa lander which would place a lander on the surface of Europa. In terms of scientific objectives for a lander mission, active sampling of Europa’s non-ice material is suggested as a top priority [3]. Also of interest is geophysical prospecting and characterization of the surface geology in situ. These missions have been estimated to cost anywhere from $1B to $3B.

Direct Fusion Drive allows much more ambitious missions for less cost than options considered by NASA. The Europa DFD mission would use a smaller launch vehicle to put the spacecraft into its interplanetary trajectory by using the DFD as an upper stage. This would allow a launch on a SpaceX Falcon 9. The DFD would be used to enter Jupiter orbit and to orbit Europa. Once in orbit, the high power available from DFD would allow high power radars to scan the surface. High power communications would greatly increase the science yield of the mission. Radioisotope thermal generators would not be needed. The spacecraft would also have the capability to include a lander if desired.

Direct Fusion Drive can be used for missions anywhere in the solar system. Missions to Titan and Enceladus have been proposed to look for life on those moons [4]. DFD would make those missions practical. It is also an excellent candidate for the 200-400 AU mission [5, 6] and other interstellar precursor missions. A flyby or even an orbital mission to a nearby star is not out of the question [7]. DFD would greatly expand the scope of robotic exploration and allow for more science missions in less time and lower cost.
## Contents

1 Europa Exploration 3
   1.1 Introduction ......................................................... 3
   1.2 Europa Clipper ...................................................... 3
   1.3 Europa Lander ....................................................... 4
   1.4 Jupiter Icy Moon Explorer ........................................... 5

2 The Direct Fusion Drive 5

3 Mission Analysis 6
   3.1 Europa Orbiter ..................................................... 6
   3.2 Europa Lander ....................................................... 10

4 DFD Program Plan 11

References 13
1 Europa Exploration

1.1 Introduction

Since its discovery in 1610, Europa has been of interest to astronomers and planetary scientists. Observations made by NASA’s Voyager and Galileo spacecraft and from Earth-based telescopes indicate that Europa’s surface is quite young, with very little evidence of cratering, and made principally of water ice.

Theoretical models of the Jovian system and Europa indicate that tidal heating may allow for liquid water or an ocean beneath Europa’s surface. Liquid water would allow life to exist on Europa below its surface. While no evidence for life exists, the potential for life makes Europa a prime target for further exploration.

This section discusses current mission concepts for exploring Europa. The missions are based on current technology. The primary challenges are to produce enough power for the science mission, do the orbit change maneuvers and to handle the radiation around Jupiter. An earlier attempt to mount a very ambitious mission to Jupiter, the Jupiter Icy Moons Orbiter (JIMO) mission was cancelled due to excessive costs. JIMO would have used a nuclear fission reactor to power both the spacecraft and the propulsion system. The mission would have required three launches and cost $16B.

Each of the three mission concepts described below involves spacecraft with limited ∆V and limited power. Issues exist with the proposed power generation means. RTGs require plutonium which is currently a difficult commodity to obtain. Solar cells will be damaged by radiation in the Jovian environment.

It is important to consider what might be achieved in the future by making relatively small investments in advanced technology like DFD. Envision what could be done with 2 MW of power on board, such as operating high power radar or transmitting high definition images or video streams. Such technology would enable revolutionary mission concepts, data collection, and discovery of our solar system.

1.2 Europa Clipper

The Europa Clipper uses a Multiple-Flyby Mission architecture that is well suited to satisfying the science objectives in a cost-effective, lowest-risk manner. A trajectory has been identified that provides globally distributed regional coverage of the Europa surface through a series of flybys. Once the flyby campaign begins, Europa is encountered every 7 to 21 days. This approach allows for high-data-rate science collection followed by days of playback time, while greater mass margins afforded by foregoing an Europa orbit insertion enable shielding to a lower radiation dose. This mission architecture is well suited to Europa Multiple-Flyby Mission instruments, which are heavy, require significant operating power, and generate considerable data. On each flyby, science data is collected for approximately one hour, leaving the remainder of the 7 to 21 days between Europa encounters for science data return and battery recharging.

Science operations for the flybys are repetitive, which leads to lower cost mission operations.

The conceptual spacecraft uses a modular architecture, which facilitates the implementation, assembly, and testing of the system. The spacecraft is 3-axis-stabilized for precise instrument pointing, and avoids solar pointing constraints by using four Advanced Stirling Radioisotope Generators (ASRGs) for power. An innovative propulsion system accommodation for an internal, Juno-style electronics vault and a nested shielding strategy provides significant protection from the radiation environment, allowing the use of 300-krad-tolerant parts.

Two missions have been studied. One uses an Atlas V 551 launch and a Venus-Earth-Earth gravity assist (VEEGA) trajectory that takes 6.4 years to reach Jupiter. The second uses an SLS launch and reaches Jupiter in 1.9 years. Both are estimated to cost $2.1B.
1.3 Europa Lander

The Europa Lander [12] would be launched on a Delta IV Heavy on a VEEGA trajectory taking 6.4 years to get to Jupiter. After Jupiter Orbit Insertion (JOI), the spacecraft energy is reduced so that EOI can occur 1.4 years later while accumulating 125 kilorads of radiation.

The Europa Lander Mission would be launched as an integrated spacecraft. The integrated spacecraft is pictured in Figure 1-2. The Landers deployable components are stowed until after landing. The integrated spacecraft would use power from the Carrier Advanced Stirling Radioisotope Generators (ASRGs) and Lander ASRGs.

Figure 1-2: Europa Lander requires 7.2 years to reach Europa orbit. The Z axis is vertical in the picture.

The Carrier has two distinct modules oriented about the Z axis from top to bottom and a 3-meter high-gain antenna (HGA) on the side of the Propulsion Module along the +Y axis; the main rocket engine is located on the -Z axis; the Propulsion Module tanks and the outrigger-mounted control thruster engines are located at mid-span; and the ASRGs for power-generation are mounted symmetrically about the main engine (ME) at the base of the Propulsion Module. After Europa Orbit Insertion (EOI), the integrated spacecraft will perform reconnaissance imaging of the potential landing sites. Ground-based analysis will aid in the site-certification process. Precision landing is required for safety with the Lander configured for pinpoint landing. After 30 days in orbit, the Lander will be released and a deorbit burn performed via a solid-rocket motor (SRM) followed by a powered terminal descent to touchdown using monopropellant thrusters. Onboard navigation uses a high-precision inertial reference unit augmented by terrain-relative navigation (TRN) using descent imaging to determine location and reachable sites. A hazard-avoidance system will ensure that the Lander is set down in acceptable surface conditions. The cost of the mission is estimated at $2.8B in FY 2015 dollars. The price of the ASRGs are $200M. Operations is $400M.
1.4 Jupiter Icy Moon Explorer

The Jupiter Icy Moon Explorer (JuIcE) is an ESA mission to explore the icy moons of Jupiter. The spacecraft is solar powered. It requires a total of \(2.6 \text{ km/s} \Delta V\). The transit time to Jupiter is 7.6 years and the total mission duration is 10.6 years. The ambitious scientific objectives require complex maneuvers near Jupiter including numerous gravity assists.

Figure 1-3: Jupiter Icy Moon Explorer showing one possible layout.

2 The Direct Fusion Drive

The scientific feasibility of nuclear fusion itself has been demonstrated by the Tokamak Fusion Test Reactor (TFTR), the Joint European Torus (JET), and the Japan Torus (JT-60). TFTR has generated a record maximum of 10.7 MW of fusion power, JET produced 16.1 MW, with a Q of \(\approx 0.6\), and JT-60 achieved an effective Q \(\geq 1.25\) (if DT were used) and a record ion temperature of 45 keV (where Q is the fusion energy gain factor or the ratio of nuclear energy produced to the energy needed to maintain the plasma). Tokamaks have many engineering challenges before they can be used in power plants but there is no question that a fusion power plant can be built. However, tokamaks, due to their low plasma \(\beta\), are not suitable for any fuels except deuterium and tritium (which is really deuterium lithium since the tritium must be bred from neutron irradiated lithium in the plant) and are not good candidates for space reactors.

The Direct Fusion Drive would be a 2 m diameter, 10 m long, steady-state plasma device heated by a novel radio-frequency (RF) plasma-heating system, enabling the achievement of sufficiently high plasma temperatures for D–\(^3\)He fusion reactions. An FRC employs a linear solenoidal magnetic-coil array for plasma confinement and operates at higher plasma pressures, hence higher fusion power density for a given magnetic field strength than other magnetic-confinement plasma devices. A linear solenoid is well-suited for producing a collimated directed exhaust stream that may be used for propulsion. A rocket engine based on the PFRC is designed to operate with a D–\(^3\)He fuel mixture though, for decade-long missions, it may be operated with a tritium-suppressed D–D fuel cycle. Both fuels produce much lower levels of neutrons than deuterium-tritium, reducing shielding mass as well as waste energy unavailable for propulsion. In the PFRC-R, waste heat generated from bremsstrahlung and synchrotron radiation will be recycled through the RF system to maintain the fusion temperature. The features of this design are:

1. Odd-parity rotating magnetic field (RMF) heating for high stability and efficient heating
2. Non-equilibrium operation for reduced neutron production
3. Operation with D–\(^3\)He or tritium-suppressed D–D
4. Electric power extraction through the RMF coils
5. Combined thrust and electric power generation
3 Mission Analysis

Two missions to Europa are considered using the DFD engine for propulsion. First, a Europa orbiter mission is designed, using a Lambert algorithm to approximate the transfer from Earth to the Jovian system. Phasing for the mission is achieved using a simplified planetary almanac. Europa’s orbit is approximated as a conic about Jupiter. The $\Delta V$ and burn times required are listed for each phase of the mission. The simplified trajectories can be refined to include a realistic burn-coast-burn scheme, more accurate celestial body positions, and additional gravitational disturbances throughout the transfer. A subsequent lander mission is also considered, which employs a bilinear tangent thrust direction programming law for the landing algorithm.

3.1 Europa Orbiter

The baseline spacecraft is taken from [11, 18]. The mass of the spacecraft is 3241 kg. This is the mass as given in the CBE column of Table C.2.4-7. Europa Multiple-Flyby Mission mass margin [11] less the ASRGs (174 kg), Ampac LEROS 1c engine (4.3 kg) and propellant for the delta-v burns (935 kg). The resulting mass is 1241 kg. The dry mass of the DFD is 2000 kg for a 2 MW engine making the total mass 3241 kg.

The mission phases are

1. Earth escape
2. Insertion into the transfer ellipse
3. Insertion into the heliocentric Jupiter orbit
Figure 2-2: DFD Core showing the details of the PFRC reactor and the linear path of the propellant flow.

4. Insertion into Jupiter Orbit
5. Insertion into Europa Orbit

Figure 3-1 on the following page shows the transfer orbit between Earth and Jupiter. Here, we have used a Lambert algorithm to approximate the transfer. Phasing of the Earth and Jupiter is accomplished using a simplified planetary almanac.

For this example mission, a grid search was performed over a period from June 3, 2032 to May 19th, 2025 determine the launch date with the lowest associated transfer $\Delta V$. The best transfer was observed to correspond to a launch date of August 2, 2034.

Figure 3-2 on page 9 shows the Jupiter insertion geometry. This section of the transfer is displayed in a Jupiter fixed inertial frame. The $\Delta V$ burn at the end of the transfer is applied such that the spacecraft enters a circular Jupiter parking orbit with a radius that is slightly larger than the orbit of Europa.

Capture around Europa is achieved by burning into circular orbit. Phasing of Europa and Jupiter is not considered for this portion of the transfer. Figure 3-3 on page 9 shows the vehicle optimization as a function of mass.

The mission design is given in Table 3-1 on the next page. The spacecraft can be lifted into a 1000 km altitude Earth orbit by a SpaceX Falcon 9 with over 2600 kg margin.

This example mission design showcases how the DFD engine can be use to provide the necessary propulsion to achieve exploration of Europa. It does not include $\Delta V$ for going into an inclined Europa orbit. In addition, the maneuvers are modeled as impulsive. A complete mission plan needs to account for the finite burn durations.
Figure 3-1: Jupiter Transfer shows the transfer orbit between Earth and Jupiter.

Table 3-1: Europa mission design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V$ Falcon 9 separation</td>
<td>3.04 (km/s) Burn Duration 3.9 (days)</td>
</tr>
<tr>
<td>$\Delta V$ First Lambert burn</td>
<td>20.89 (km/s) Burn Duration 30.1 (days)</td>
</tr>
<tr>
<td>$\Delta V$ Second Lambert burn</td>
<td>17.95 (km/s) Burn Duration 25.3 (days)</td>
</tr>
<tr>
<td>$\Delta V$ Jupiter orbit insertion</td>
<td>4.74 (km/s) Burn Duration 6.1 (days)</td>
</tr>
<tr>
<td>$\Delta V$ Europa orbit insertion</td>
<td>1.37 (km/s) Burn Duration 1.7 (days)</td>
</tr>
<tr>
<td>$\Delta V$ Total</td>
<td>48.01 (km/s) Burn Duration 67.1 (days)</td>
</tr>
<tr>
<td>Mass Total</td>
<td>5984.1 (kg)</td>
</tr>
<tr>
<td>Mass Fuel</td>
<td>2637.6 (kg)</td>
</tr>
<tr>
<td>Thrust</td>
<td>30.0 (N)</td>
</tr>
<tr>
<td>Power</td>
<td>2.0 (MW)</td>
</tr>
<tr>
<td>Mass Falcon 9</td>
<td>8687.0 (kg)</td>
</tr>
<tr>
<td>Launch Date</td>
<td>08/02/2034 00:00:00:00</td>
</tr>
</tbody>
</table>
Figure 3-2: Jupiter Insertion directly into a circular Jupiter orbit.

Figure 3-3: Optimal spacecraft shows that the total mass for a 2 MW power plant the thrust is 30 N, the total mass is 5984 kg and the optimal exhaust velocity is 82 km/s.
3.2 Europa Lander

The DFD spacecraft can fly at very low altitudes to facilitate a lander mission. The atmospheric density and drag is very low Figure 3-4 so the spacecraft can fly at altitudes just skimming the surface. Europa lacks high mountains but does have tidal distortions of up to 100m. The Conamara Chaos region of Europahas has ice cliffs over 100 metres high. It might be possible to fly within 1 km of the surface. The required velocity change for direct descent landing drops with altitude as shown in Figure 3-5. This decreases the fuel mass and the size of the engine.

Figure 3-4: Europa Atmospheric density and drag are very low.

Figure 3-5: Landing Velocity Change decreases with altitude. The mass ratio is based on an ECAPS HPGP engine.

The thrust direction for the landing algorithm is determined using the bilinear tangent law, and assuming a flat Europa. As an example, a simulation of a descent from 4.7 km is shown in Figure 3-6 on the following page.

The magnitudes of the acceleration perturbations due to the gravitational influence of Jupiter and the Sun are on the
Figure 3-6: Europa Landing Simulation using a bilinear tangent thrust direction programming law and a thrust equal to three times the gravitational surface acceleration on Europa.

order of $10^{-4}$ km/s$^2$ and $10^{-7}$ km/s$^2$ respectively. For reference, the gravitational force due to Europe is on the order of $10^{-3}$ km/s$^2$. A refined landing algorithm that accounts for these disturbances should be considered in future work. The lander simulation details how DFD enables advanced mission concepts, like a Europa lander.

4 DFD Program Plan

PSS and PPPL have developed a complete DFD development program designed to produce an operating fusion reactor within a 12-year time frame. The current work is in the experimental stage. Two additional research devices would be built, PFRC-3 and PFRC-4. PFRC-4 would demonstrate fusion power generation. It is estimated that the total cost of this program would be $76M. This development plan is much shorter and the cost much less than that for Tokamak fusion. This is due to the simple geometry and the small size of the machines. Furthermore, the experimenters do not have to handle tritium, an expensive process.

Figure 4-1: DFD Program Plan resulting in a burning fusion reactor by 2023. i-temp is ion temperature and e-temp is electron temperature.

<table>
<thead>
<tr>
<th>Machine</th>
<th>PFRC-1</th>
<th>PFRC-2</th>
<th>PFRC-3</th>
<th>PFRC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objectives</td>
<td>Electron Heating</td>
<td>Ion Heating</td>
<td>Heating above 5 keV</td>
<td>D-He3 Fusion</td>
</tr>
<tr>
<td>Goals/Achievements*</td>
<td>3 ms pulse* 0.15 kG field* e-temp = 0.3 keV*</td>
<td>0.1 s pulse* 1.2 kG field i-temp = 1 keV</td>
<td>10 s pulse 10 kG field i-temp = 5 keV</td>
<td>1000 s pulse 60 kG field i-temp = 50 keV</td>
</tr>
<tr>
<td>Plasma Radius</td>
<td>4 cm</td>
<td>8 cm</td>
<td>16 cm</td>
<td>25 cm</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$2M</td>
<td>$6M</td>
<td>$20M</td>
<td>$50M</td>
</tr>
</tbody>
</table>

Work to support the Europa mission would be

1. Develop a detailed mission plan and simulate the entire trajectory. The finite duration of each burn would be
modeled in developing the trajectories. Science objectives would be factored into the trajectory plan. Jupiter perturbations would also be included.

2. Develop a detailed conceptual design for the 2 MW engine. Produce a specific power for the engine. Fuel tank design for long-duration storage of deuterium and helium-3 would be studied.

3. Investigate mission options given the availability of 2 MW of electric power in Europa orbit.

Figure 4-2 gives the proposed budget for the study. This work would augment the work in the DFD program plan given in Figure 4-1 on the preceding page.

**Figure 4-2: Europa mission budget** for a six month study.

<table>
<thead>
<tr>
<th>Task</th>
<th>2015 Tasks</th>
<th>PSS</th>
<th>PPPL</th>
<th>Total FTE</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mission Plan</td>
<td>0.25</td>
<td>0.00</td>
<td></td>
<td>0.25</td>
<td>$65,000</td>
</tr>
<tr>
<td>2 Engine Design</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
<td>0.50</td>
<td>$169,000</td>
</tr>
<tr>
<td>3 Mission Options</td>
<td>0.25</td>
<td>0.00</td>
<td></td>
<td>0.25</td>
<td>$65,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.75</strong></td>
<td><strong>0.25</strong></td>
<td></td>
<td><strong>1.00</strong></td>
<td><strong>$299,000</strong></td>
</tr>
</tbody>
</table>
References


